" THE FASCINATING RAINBOWS " A CHRONOLOGICAL STUDY WITH MODERN EXPLANATION

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"THE FASCINATING RAINBOWS "

A CHRONOLOGICAL STUDY WITH MODERN EXPLANATION

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ABSTRACT

Folklores as well as scientific theories have tried to explain the eye catching phenomena of rainbows ."But rainbows differ among themselves as one tree from another and the 'explanations' generally given of The Rainbow (in text books) may well be said to explain beautifully that which does not occur and to leave unexplained that which does " .The purpose of this paper is to examine the work done by many scientists from ancient to present time in chronological order and to arrive at the state of art conclusion . The study starts at Aristotle's explanation of rainbow using "Meteorological Sphere" and ends at Nussenzevig theory of Rainbow as a macroscopic light-tunneling effect. It also includes an ancient Indian explanation of Varahmihir in his book BRIHAT SAMHITA and the modern view of Rainbow as diffraction catastrophes. Finally a comprehensive discussion of the theories is presented.

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INTRODUCTION

Rainbows are most beautiful sight in the sky. Poets and philosophers alike have marvelled at them for centuries and honoured them innumerable times in song and verse. The ancient Germans and Japanese thought that the rainbow was a bridge for gods to take a trip around the world . For Babylonians , the rainbows is the necklace of love goddess Ishtar .In the famous epic of Homer ,in Iliad the goddess Iris takes to Aphrodite from the battle area to Olympus by following the Rainbow .In the ancient Chinese and Indian literature various classifications of rainbows are found and They were used as astrological tools to predict future, e.g. ,

जलमध्येऽनावृष्टिर्भुवि सस्यवधस्तरौ स्थिते व्याधिः ।
वाल्मीके शस्त्रभयं निशि सचिववधाय धनुरैन्द्रम् ॥५॥

"A rainbow seen in the middle of water causes drought ; on land , destruction of crops ; on a tree , disease ; on an anthill, danger from weapons ; and at night, death of minister ".

As far as scientists are concerned the rainbow has served as a touchstone for testing the theories of optics – from the geometrical to quantum .They have devised some of the most powerful tools of mathematical physics explicitly to deal with problem of the rainbow . The ordinary rainbow seen after rain of shower or in the spray of waterfall is a group of circular or nearly circular arcs of colours, whose common centre is the line connecting the observers eye with the source of light .The most brilliant bow , known as primary consists of

fixed sequence of colours ; Violet is innermost bending gradually with various shades of Blue, Green , yellow and Orange with Red outermost .

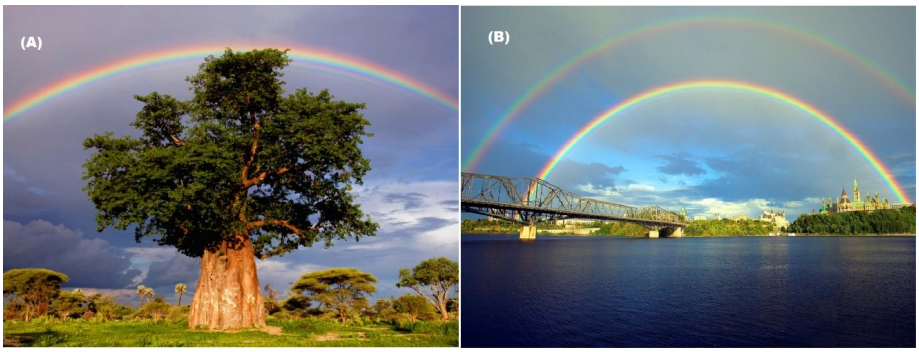


Fig.:-01 (A) Primary Rainbow
(B) Primary & Secondary Rainbow with Alexander's dark band

Higher in the sky than the primary bow is the secondary bow in which colours appear in in reverse order , with Red innermost and violet outermost .The region between the two bows is considerably darker than the surrounding sky and has been given the name Alexander's dark band , after the Greek philosopher Alexander of Aphrodisias who first described it in about 200 AD .

Another feature that is sometimes seen is the presence of supernumerary arcs . These are series of faint narrow bands usually pink and green alternately on the inner side of the primary bow and at times on the outer side of secondary bow. The records of close observations of rainbow show that not even the colours are always the same; neither is the band of any colour of constant angular width ; nor the total breadth of the several colours at all uniform ; similarly the purity and brightness of different colours are subject to large variations .

The greatest contrast is between the sharply defined brilliant rainbow of retreating thunderstorms and that ill defined faintly tinged bow that sometimes appear in the mist - the " White bow or Fog bow" .

Also there have been at least two recorded observations in the past of vibrations in the rainbow caused by thunder.

There have been no verified observations of any but the first two rainbows in a natural landscape . Yet in 1868, Billet was able to detect first 19 rainbows from a thin stream of water which was illuminated with various coloured lamps . In a recent report , an apparatus has been described that can visualize the creation of rainbows using a cylinder of acrylite glass . The apparatus allows one to observe rainbow up to the sixth order. It is claimed that with an intense light source and a good camera ,it is possible to use the apparatus as a classroom demonstration .

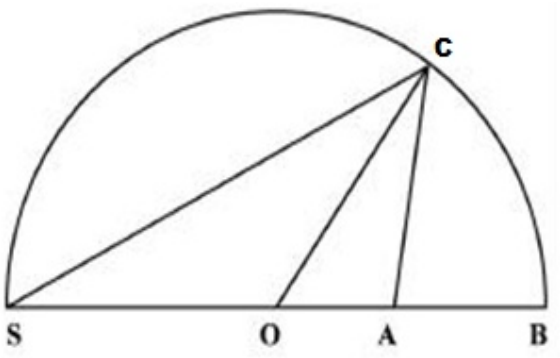
In this paper we present a brief review of various theories advanced by scientists of different ages in a chronological order .

Aristotle (385 BC -322 BC):-

Aristotle, a Greek philosopher and scientist, was perhaps the first one to have attempted a rational explanation of rainbow. He proposed that the rainbow is actually an unusual kind of reflection of sunlight from clouds .He believed in what he called "meteorological sphere" with dense cloud inside .The Rainbow occurs if after reflection from dense clouds in the "meteorological sphere", the rays of sunlight reaches the observers eye which lies at centre of the hemispherical shape of the bow .

Aristotle thus can be given the credit to have perceived that the rainbow is not a material object with a definite location in sky but rather a set of directions along which light is strongly scattered into the eyes of observer

.His explanation of Rainbow were effective for centuries and most popular in Islamic world.



S = Sun, O = Observer, C = Cloud

Fig.:-03 Aristotle's Meteorological Sphere

Seneca the Younger (4BC -65 AD):-

Lucius Annaeus Seneca, a Roman philosopher, and statesman, in his book 'Naturales *Quaestiones* 'explains the causes and functional mechanisms of natural phenomena like rainbows. His discussion of the rainbow is one of the most detailed and vivacious in the whole volume of his book '*Naturales Quaestiones* ' It takes the form of a sustained argument, in which he cites various authorities, and replies to objections brought by a supposed opponent to his thesis, which is that the rainbow is unquestionably an image of the sun received in a very moist cloud which has the shape of a round concave mirror and appears opposite to the Sun.

Varahmihir (505 AD – 587 AD):-

Varahmihir , an Indian astronomer, mathematician, and astrologer explained colourful band of rainbow as dispersion of sun light through moist air in atmosphere.

सूर्यस्य विविधवर्णाः पवनेन विघट्टिताः कराः साभ्रे ।
वियति धनुःसंस्थाना ये दृश्यन्ते तदिन्द्रधनुः ॥१॥

अच्छिन्नमवनिगाढं द्युतिमत् स्निग्धं घनं विविधवर्णम् ।
द्विरुदितमनुलोमं च प्रशस्तमम्भः प्रयच्छति च ॥३॥

In Chapter -35 (*INDRAYOUDH LAKSHANADHAYAH)* of his book ' BRIHAT SAMHITA , He not only explained rainbow and its types as primary & secondary but exemplified the divination in best way . He draws up meticulous list of signs which indicate the arrival of rain , flood, draught, Storms and earthquake and many other forecasts based on rainbow.

Ibn al-Haytham (965 – 1039):-

Abū Alī al-Ḥasan ibn al-Ḥasan ibn al-Haytham, an Arab Muslim, polymath and philosopher has been accepted as the greatest scholar of optics of all times and was also called as the second Ptolemy .He carried out successfully refraction experiments and extensive studies on the subject. Ibn al-Haytham treated the formation of rainbow in an article *"Maqala Fi Al-Hala Wa Qaws Quzah"*. In this article he explained the formation of rainbow as an image at a concave mirror. If the rays of light coming from a farther light source reflected to any point on axis of the concave mirror, they form concentric circles about that point. He, therefore, concluded that the rainbow is formed as a result of the reflection from the cloud. Although it is a different approach, it does not contribute much to the problem. Whether the cloud is plain or concave, it is not significant for the correct understanding, since the approach is merely based on reflection. He made no significant contribution to the problem of the formation of the rainbow. However, his optical studies in general and particularly his success in geometrical optics had a great influence on his successors.

Ibn Sina (980-1037):-

Abu Ali al-Ḥusayn ibn ʿAbd Allah ibn Sina (Avicenna) , a Persian polymath, is regarded as one of the most significant thinkers and writers of the Islamic Golden Age. His study of rainbow is not much different from Aristotle's study. According to Ibn Sina, rainbow is formed as a result of the reflection of light from the small transparent dewdrop particles dispersed in wet air rather than in the cloud. We can say that Ibn Sina's only success was that he gave relatively less importance to the role of the cloud, which was very important in Aristotle's account of the rainbow. The idea of using the dew instead of the cloud provided

him the possibility to examine the phenomenon geometrically. Unfortunately, Ibn Sina did not succeed either. His explanations of the secondary rainbow are not coherent. For him, the light at higher levels, being much closer to the sun, is reflected more strongly, so the red colour is formed. Accordingly, the outermost arc of the secondary rainbow must be red. However, it is violet. This indicates that Ibn Sina's explanation on the formation of the secondary rainbow was wrong. But his general observations on the problem were significant with respect to the fact that they provide more knowledge about the topic.

Shen Kuo (1031 -1095):-

Shen Kuo , a Chinese polymath and statesman of the Song dynasty, in his book "*Men Qi Bi Ji* " offered an explanation of rainbow and atmospheric refraction . He also said that position of rainbow was opposite to that of sun , hence an evening rainbow always appear in east. He explained rainbow as phenomenon of atmospheric refraction.

Roger Bacon (1214-1294):-

Roger Bacon , an English philosopher and Franciscan friar, placed considerable emphasis on the study of nature through empirical methods. He wrote in his Book "*Opus Majus* "about experiments with light shining through crystals and water droplets show the colours of the rainbow. In addition, Bacon was the first to calculate the angular size of the rainbow. He stated that the rainbow summit cannot appear higher than 42° above the horizon.. He explained the primary rainbow, noting that when sunlight falls on individual drops of moisture, the rays undergo two refractions and one reflection before transmission into the eye of the observer. He explained the secondary rainbow through a similar analysis involving two refractions and two reflections.

Qutb al-Din al-Shirazi(1236-1311):-

Qutb al-Din al-Shirazi , a Persian astronomer , gave fairly accurate explanation for the rainbow phenomenon. This was elaborated on by his student, Kamāl al-Dīn al-Fārisī who gave a more mathematically satisfactory explanation of the rainbow. He "proposed a model where the ray of light from the sun was refracted twice by a water droplet, one or more reflections occurring between the two refractions". He conducted an experiment with a water-filled glass sphere and showed the Rainbow phenomena; additional refractions due to the glass could be ignored in his model.

Theodoric of Freiberg (1250- 1310):-

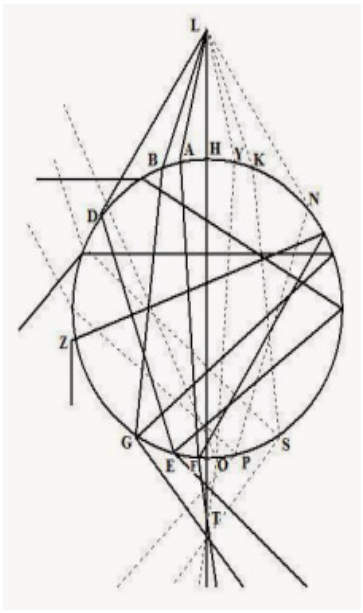
Theodoric of Freiberg, a German theologian and physicist, wrote a treatise on the rainbow *De iride* around 1310. His innovations derived from his own extensive experimental investigations in which he used prisms, screens, and spherical flasks filled with water. Theodoric regarded a spherical flask as a model of a raindrop in a cloud. He observed that different colors appeared as he would raise the flask higher or lower. By covering certain portions of the flask at a time, one after another, to see where the light would come out, Theodoric determined the path that light follows from the Sun through the drop to the human eye to create a rainbow. Moreover, Theodoric also worked out the path light follows in creating the secondary rainbow. Theodoric, therefore, concluded that, as a result of the three or four step process of refraction and reflection, one drop of water would send only one color of light to the eye of the observer. The rainbow results from a combination of many drops of water in a cloud at different positions from a center, where the drops at each distance from the center send a particular color of the rainbow.

Theodoric's explanation of the primary and secondary rainbows as a result of these three and four-step processes of refraction and reflection is still regarded as correct.

Kamal al-Din al-Farisi (1267–1319):-

Kamal al-Din al-Farisi, a prominent Persian contributor of optics, did not write separate book on the formation of rainbow. But we can have information about his studies from his *Tanqih al-Manazir*, which is a commentary on Ibn al-Haytham's *Kitab al-Manazir*. In this commentary book, Kamal al-Din al-Farisi dealt with Ibn al-Haytham's work on Burning Spheres. There, Ibn al-Haytham had postulated some principles for Burning Spheres that Kamal al-Din al-Farisi tried to interpret.

According to Kamal al-Din al-Farisi, when the sunrays fall on a reflective or refractive surface, they reflect from or refract to another point. If there is another reflective or refractive surface, they will continue reflection or refraction. This may happen several times. But through these processes the structure of the ray never changes but remains the same. When a transparent sphere is placed in front of an eye, a cone occurs with the axis of a straight line between eye and the surface in front of it. Rays coming from the axis pass through the sphere without changing the direction, that is, they do not deviate, but the others deviate because of density of the sphere.



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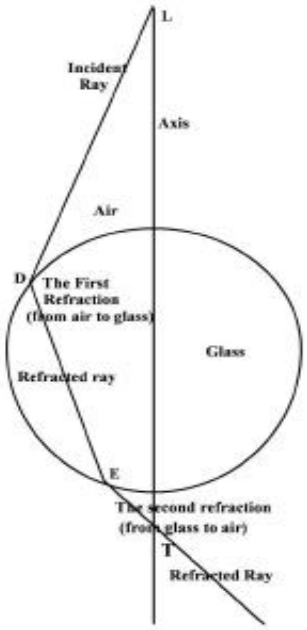

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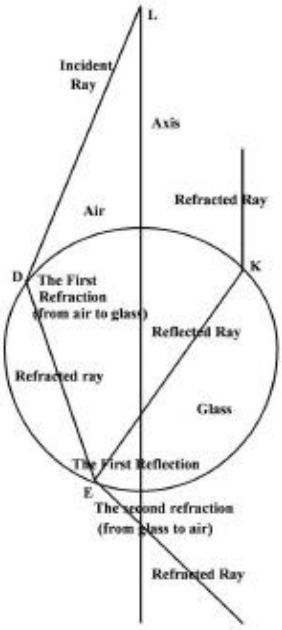

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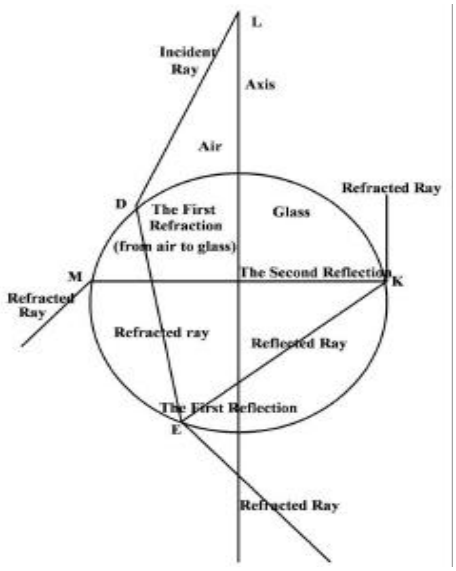

(D)

Fig.:- 04 (A) The paths of rays in a transparent sphere (B) Double refraction of a ray in a transparent sphere (C) Double refraction and one reflection of a ray (D) Double refraction and double reflection of a ray

Kepler (1571-1630):-

Johannes Kepler , a German mathematician, astronomer, and astrologer in his book "*Mysterium cosmographicum* " elaborated self analysis and provided Glimpse of ideas on Rainbow. In his early explanation of rainbow he used strange mixture of Aristotelian colour theory and Pythagorean Numerology.

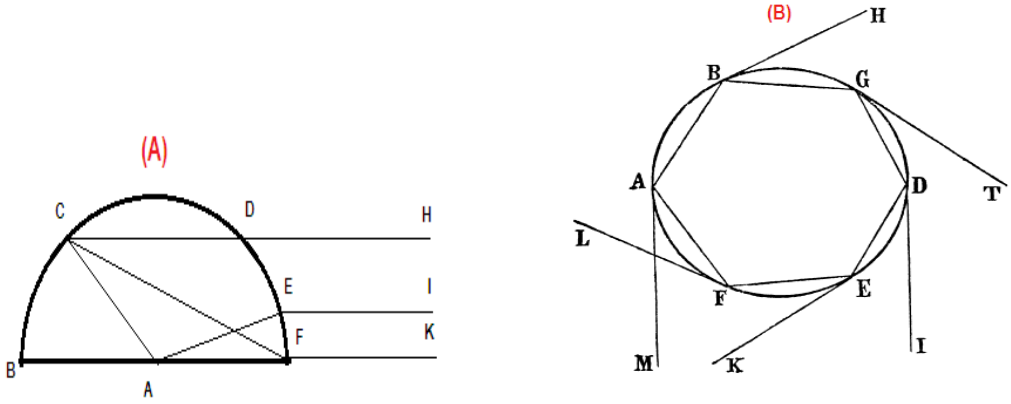

Fig.:-05 (A) Keplers early explanation for formation of Rainbow as reflection from spherical cloud (B)Geometrical representation of kepler's combined Reflection refraction theory

He said that the Rainbow is produced due to reflection of light rays from spherical cloud and the Sun. Later he explained rainbow as a phenomenon based on refraction and reflection in individual drop.

Rene Descartes (1596-1650) :-

Rene Descartes, a French philosopher, mathematician and scientist further advanced explanation of rainbow knowing that the size of raindrops did not appear to affect the observed rainbow .He experimented with passing rays of light through a large glass sphere filled with water. By measuring the angles that the rays emerged, he concluded that the primary bow was caused by a single internal reflection inside the raindrop and that a secondary bow could be caused by two internal reflections. He supported this conclusion with a derivation of the law of refraction and correctly calculated the angles for both bows. His explanation of the colours, however, was based on a mechanical version of the traditional theory that colours were produced by a modification of white light.

Isaac Newton (1643-1727):-

Sir Isaac Newton, an English physicist and mathematician, demonstrated that white light was composed of the light of all the colours of the rainbow, a glass prism could separate it into the full spectrum of colours and rejected the theory that the colours were produced by a modification of white light. He also showed that red light is refracted less than blue light, which led to the first scientific explanation of the major features of the rainbow. However Newton's corpuscular theory of light was unable to explain supernumerary rainbows and a satisfactory explanation was not found until Thomas Young realised that light behaves as a wave under certain conditions, and can interfere with it.

George Biddell Airy (1801-1892):-

Sir George Biddell Airy , an English mathematician and astronomer , explained Rainbow on the basis of principle of wave propagation . He approximated the scattered wave front shape with a cubic form and developed an analytic expression for the intensities of scattered light in rainbow in terms of what are now called Airy integrals or functions. Airy's theory gives satisfactory predictions of the observable features of white light rainbows for rather large raindrops. The intensity distribution predicted by Airy function is analogous to diffraction pattern appearing in the shadow of a straight edge.

Gustav Mie (1869-1957):-

Gustav Adolf Feodor Wilhelm Ludwig Mie , a German physicist explained the oblique sun angles coming through atmosphere tend to cause scattering of lower wavelength of visible light. He used partial- wave method developed by lord Rayleigh and others for the problem of scattering of sound wave by a sphere. and evaluated the sum of several thousand complicated terms .He presented Modern Physical description of Rainbow based on Mie Scattering in 1908.

Peter J. W. Debye (1884-1966):-

Peter J. W. Debye, an American physicist, gave precise mathematical formulation of the Rainbow by computing the scattering of an electromagnetic plane wave by a homogeneous sphere with help of Debye-

series expansion of the partial-wave scattering. It shows existence of an exact solution to the scattering problem, which can be used to determine all features of rainbow by including large number of terms in the series. Later an improved technique known as Watsons transformation of partial wave or as the complex angular momentum(CAM) method was applied to the Rainbow problem which only resulted in obtaining Airy's approximation of rainbow as a limiting case .

Herch Moyses Nussenzveig (1933- Present):-

Herch Moysés Nussenzveig, a Brazilian physicist, professor at Federal University of Rio de Janeiro provided modern overview of Rainbow problem. In 1965 he developed an improved version of Watson's method and applied it to the rainbow problem with great success . In 2002 Nussenzveig made detailed analysis of rainbow problem to determine that these effects arise from quantum mechanical tunnelling resonance and concluded that rainbow as a macroscopic light tunnelling effect .

THE RAINBOW AS A DIFFRACTION CATASTROPHE

An alternative way of describing rainbow phenomena is by way of "Catastrophe Theory" , the term coined by Trinkaus and Drepper .Catastrophes are at the heart of many fascinating optical phenomena . Rainbow is the ray catastrophe where light rays become infinitely intense . The wave nature of light resolves infinities of ray catastrophe while drawing duplicate interference pattern such as supernumerary arcs of the rainbow .

Light rays from the Sun enters water droplets floating in air . After two refraction and one reflection rays reach an observer. Above critical observations angle the rays arrive , whereas below the angle two rays strike the observer . A bright bow, The Rainbow , appears at the critical angle because here the cross-section of light rays diverge . The direction of light ray is proportional to the gradient of the phase. The rainbow thus presents a singularity of gradient map which is known as catastrophe of Thom and Arnol'd type.

DISCUSSION

Though Rainbows are only meteorological phenomena then sheer beauty has captured the attention of poets ,philosophers rainbow right from Aristotle to present age . But as is evident from above study most of the earlier theories either incorrect or found wanting. .

As the laws of reflection of geometrical optics got established the main features of Rainbow got explained in terms of two refraction , one or two internal reflection and minimum deviation caused by the water droplets suspended in air after the rains . Descartes and Newton between them were able to explain the existence of primary and secondary rainbow and the dark band that separates them.

They calculated the angular positions of these features and described the dispersion of the scattered light into a spectrum using only geometrical optics .However they could not explain the supernumerary arcs.

The optical effect underlying the supernumerary arcs was in 1803 by Thomas Young , who showed that light is capable of interference which is a wave phenomenon With Young's interference theory all the major features of rainbow could be explained as least in a qualitative ,and approximate way what was lacking was a quantitative mathematical theory capable of predicting the intensity of scattered light as a function of droplet size and scattering angle . Subsequently three major quantitative theories of the rainbow emerged. The airy approximation , the exact solution as partial wave series by Mie scattering and the rainbow terms in the complex angular momentum (CAM) method also known as Watson method . In 1975 Vijay Khare of University of Rochester made a

detailed comparison of three theories of the rainbow . The Results are shown in the figure .

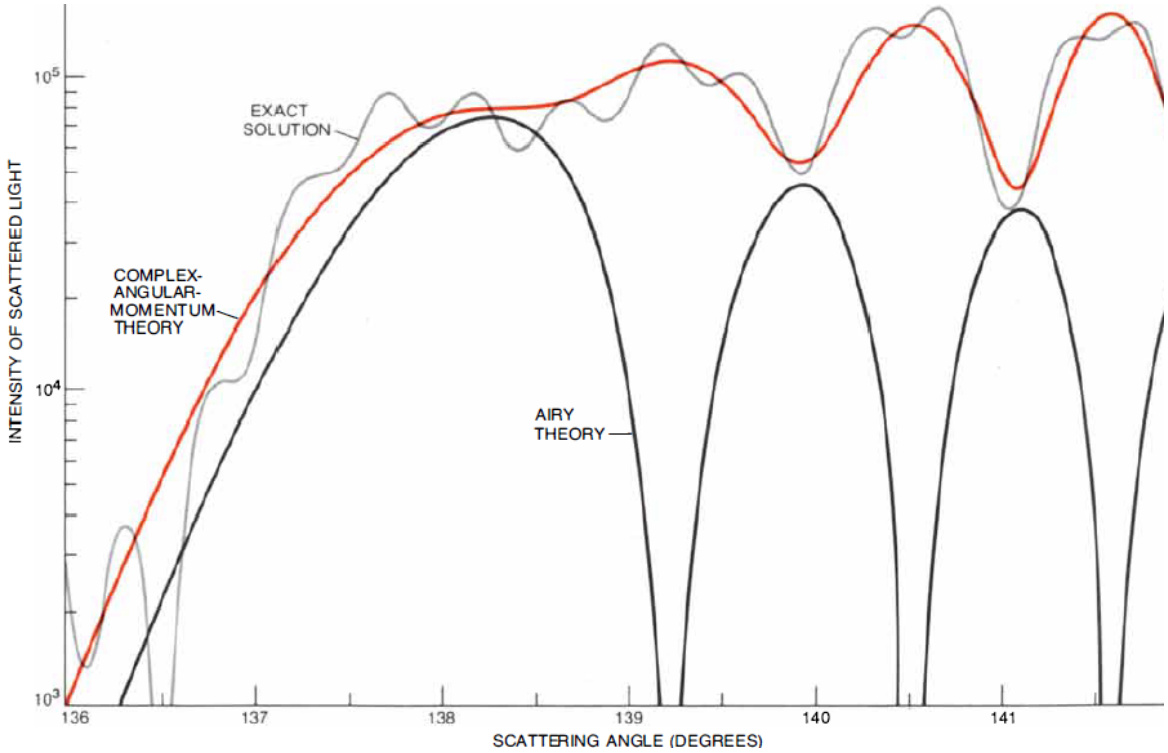

Fig: Quantitative Comparison of intensities of rainbow as a function of scattering angle for Airy approximation, the “exact" solution, obtained by a computer summation of the partial-wave series and the rainbow terms in the complex-angular momentum method

In terms of large scale features such as the primary bow, the supernumerary arc and the dark side diffraction pattern , The complex angular momentum result agrees quite closely with exact solution

Finally the problem of rainbows has been addressed by the quantum theory of light and the catastrophe theory . As a result the fascinating rainbows are now treated as the macroscopic light tunneling effect or as the diffraction catastrophe of Thom and Arnol’d .

CONCLUSION

The Rainbows , the same old Rainbows of Aristotle ,of Varahmihir of Newton and of Nussenzveig have been challenging the best of the brains of all ages and yet the chapter is not closed . We hope the fascinating rainbows will keep on shining with all its glory , which by the way is another fascinating meteorological phenomena formed in part from the shadow of a rainbow .

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